Master Thesis for the Master of Philosophy in Environmental and Development Economics

PROMOTING WIND POWER IN CHINA

Welfare Analysis of Mandated Market Share (MMS)

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Abstract

Along with people's profound recognition of the importance of wind power, countries are seeking for feasible and effective policy regimes or mechanisms to explore and develop wind power, and China is no exception. Therefore, Mandated Market Share (MMS) policy on promoting wind power is selected as the focus of this study. A welfare-maximizing model is first developed and is trying to represent a real power market, where the wind power and the coal-fired power are used simultaneously. And then, the welfare analysis is used to investigate the social optimization problems with and without MMS. Also, the policy is investigated in competition and monopoly market organizations to see which market organization is more efficient with MMS. Finally, through welfare analysis and the relevant discussion this study tells us why we need MMS policy on promoting wind power.

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1 Introduction

China is a country not only with a huge population but also with a fast growing economy. The fast growing economy causes a huge increase in the electricity consumption. According to Xinhua News Agency, with an economy growing at 9.8%, the overall electricity consumption in China goes up by 13.2% in 2005, leading to a severe problem of how the country powers its factories, businesses, and households for the coming decades. As we know, China's power industry is mainly relying on coal-fired power. According to Zhang and Zhao (2006), electricity output in China reached 2474.7 billion kwh in 2005, within which, coal-fired electricity was 2018 billion kwh, accounting for 81.5%; hydropower 395.2 billion kwh, 16.0%; nuclear power 52.3, 2.1%; other resources such as wind, solar and tidal power 9.2 billion kwh, 0.4%.

The traditional power choice – coal – however, causes significant environmental problems. The sulfur dioxide emission from burning coal is one of the direct causes of air pollution. Some research shows that 40,000 people in China die each year from air pollution (Yu, 2005). As coal is non-renewable resource, once used up, they will take hundreds of millions of years to regenerate, which would result in resource depletion. The pollutants from the burning of coal would also cause acid rain and greenhouse effects (EEC, 2005). Chinese current power sector is under a double pressure from economic growth and environmental protection. Changing the energy sources structure of electricity consumption and seeking alternative energy sources therefore are definitely crucial for the development of China's power industry.

Being a clean and renewable resource, wind energy has received much attention recently as an alternative to meet the increasing demand of electricity and to relieve environmental problems at the same time. Compared to coal-fired power, wind power is the one in line with the principle of sustainable development. Wind power has two key advantages. One is that wind power generates no pollution so it does no harm to environment, public health, particularly air quality. The other is that wind comes from nature. We may say that on a large scale it is unlimited in terms of supply. According to the estimation, if China develops one half of its exploitable wind potentialities, it could generate power about 275 billion kwh each year, displacing the need for 135 million tons of coal and reducing 2 million tons of sulfur dioxide and 70 million tons of carbon emission (Lew and Logan, 2001); if China devotes all its efforts to the development of wind power, the intending production of wind power could be three times more than the current national demand of electricity (Mao, 2006).

Currently, wind power, as new energy, has become a hot topic in the world. A number of researches on wind power were systematically discussed in literatures. (Gipe, 2004; Beith, *et al.*, 2004; and Mathew, 2006), but most of them focused on technological aspects. However, in practice, energy strategies are not made merely on the basis of technical feasibilities. The economic aspect also plays an important role in making decisions. We found some text on economics of wind power in Mathew's book (2006). He uses net present value (NPV) approach to explain how to make an investment decision from the perspective of enterprise. Of course, economic issues of wind power are multidimensional.

Along with people's profound recognition of the importance of wind power, a few countries have constructed relevant policy regimes or mechanisms to explore and develop wind power. It is generally known that policy regimes of wind power vary wildly across countries, but there are two fundamentally different policy regimes in the leading wind power countries. As mentioned in the Asia Alternative Energy Program's working paper published by the World Bank (2000), one policy regime is that the government sets the price and the market determines the quantity (such as German Feed-in Law[1]); the other is that the government sets the quantity and the market determines the price (such as

[1] According to the World Bank, under an electricity feed-in-law, electric utilities are obligated to purchase any electricity generated with renewable resources at fixed, minimum prices. These prices are generally set higher than the regular market price, and payments are usually guaranteed over a specified period of time. (see http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTENERGY/EXTRETOOLKIT)

Mandate Market Share). A proper policy regime is indispensable. For example, Germany led the world with 18,428 MW and its good development of wind power should be somewhat attributed to a favorable policy regime, the so-called "Feed-in-Law" (GWEC, 2006).

In this study, I will mainly perform welfare analysis to investigate the development of wind power by introducing Mandate Market Share (MMS) policy. According to the World Bank, MMS policy mandates that a certain share or absolute quantity of electricity is supplied from renewable energy. In other words, the government sets a target and the market determines the price (see http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTENERGY/EXTRETOOLKIT). I'm interested in MMS not only because it is a policy aiming at promoting the development of renewable energies which is in line with current China's energy strategy of taking renewable energy as the first priority, but also because there are some relevant researches on MMS policy done in China (Ren, *et al.*, 2002; Zhang, 2003; Guo, 2003; Ren, 2005; and Xu, 2005). Unfortunately most of these researches are verbal. The key difference of this study from previous researches is that I would develop a welfare-maximizing model and try to represent a real power market (such as Inner Mongolian power market), where wind power and coal-fired power are used simultaneously.

The information of policies and updated statistics, in this study, has been acquired mostly from the Internet because of its convenience. However, when using the electronic sources in social science study, attention should be paid to the origin of the website. Thus, only reliable websites of international media, governments, non-governmental organizations (NGOs), and international institutions are selected as sources.

The main text, in this study, starts in Chapter 2 where I provide some useful concepts and background knowledge of wind power. Chapter 3, 4 and 5 present the design of my study. The basic welfare-maximizing model is constructed in Chapter 3. The welfare analysis is performed to investigate the social optimization problems with and without MMS policy in Chapter 4. Then MMS policy will be investigated in two different market organizations in Chapter 5. In Chapter 6 is a brief discussion on why we choose MMS and the policy recommendations on promoting wind power for an example city, Inner Mongolia, which has similar power market with the modeled one. In Chapter 7, thesis finishes with the conclusion of what has been done and suggestions for future research.

2 Background

"Environmental resources are described as renewable when they have a capacity for reproduction and growth" (Perman, *et al*., 2003). Fisheries, forests, water and atmospheric system can be descried as renewable stock resources. On the other hand, wind, solar, wave and geothermal energy belongs to renewable flow resources. Wind energy is clean renewable resource. Wind could produce wind power. Wind power is the conversion of wind energy usually through using wind turbines.

2.1 Wind energy

Wind energy is a kind of kinetic energy generated by moving air. The kinetic energy available is higher at a higher wind speed. Recently, wind energy is being widely known by people and developing fast, since it may produce less pollution and have little negative impact on environment (ECC, 2005).

Wind power density

A meteorological report (Xue, *et al*., 2001) provides the formula for calculating wind power, namely, wind power density, D, is as follows:

$$D = \frac{1}{2}\rho v^3 \qquad (2.1)$$

Where ρ is air density measured in kg/m^3; v is wind speed measured in m/s. Due to the randomicity of wind speed, estimating the average wind power density must base on the long-time observation data.

Wind speed and electricity

The supply of wind power is intermittently provided by nature. Hence, it is necessary to build reserve capacity to ensure the reliable supply of wind power. Wind-powered turbines make use of kinetic energy to power a generator to produce electricity. For turbines, the effective wind power is generated at an interval of wind speed from start wind speed to stop wind speed (Xue, *et al*, 2001). There is no electricity produced with either an overlow wind speed or with an overhigh wind speed. By revising the formula applied in Gabrielsen, *et al*. (2005), the potential production for wind power during period t, e_t^{wind} can be calculated as follows:

$$e_t^{wind} \leq a_t \bar{v}_t^{\,3} \qquad (2.2)$$

Where a_t, represents all other factors, except wind speed, during period t, and it represents the production capacity in wind plants; $\bar{v}_t$ is the average effective wind speed during period t. We would represent the whole term, $a_t \bar{v}_t^{\,3}$ as q_t for simplification. Then, the relationship between the wind power product and the wind speed is:

$$e_t^{wind} \leq q_t \qquad (2.3)$$

<u>The utilization of wind power</u>

There are two ways of utilizing wind power in the world. One is off-grid utilization and the other is in-grid utilization. Off-grid utilization is used as an independent power generation system which is often built in rural areas. Usually, the power generation capacity of the off-grid generation system is smaller than that of the in-grid one. In this study, we will focus on in-grid wind power generation system.

2.2 Wind power in the world

Wind is the world's fastest growing energy source today. Installed capacity in 2005 grew by 40.5% so that the total global installed capacity at the end of the year was 59,084 MW. Those countries with the highest total installed capacity are Germany (18,428 MW), Spain (10,027 MW), the USA (9,149 MW), India (4,430 MW), and Denmark (3,122 MW). The other countries, including Italy, the UK, China, Japan, the Netherlands and Portugal, have reached the 1,000 MW mark (GWEC, 2006). The top-ten countries, leading in wind energy generation, are listed in Table 2.1.

Table 2.1 *Global leaders in wind energy generation in 2005*

Country	Installed capacity, MW	Percentage
Germany	18,428	31.19%
Spain	10,027	16.97%
The USA	9,149	15.49%
India	4,430	7.50%
Denmark	3,122	5.28%
Italy	1,717	2.91%
The UK	1,353	2.29%
China	1,260	2.13%
Japan	1,231	2.08%
The Netherlands	1,219	2.06%
Other regions	7,148	12.10%
The sum of the world	59,084	100%

As we mentioned in the previous chapter, the development of wind power in the world-leading countries are somewhat attributed to their appropriate policy regimes. They designed and established different policy regimes according to their own market status. The most common incentive mechanisms work as fixed price tariffs which are functioned in Germany, Spain and Denmark and compulsory renewable quota which are now in use in 20 U.S. states and several other counties as well, including Italy, the UK, Japan and Australia.. However, all incentives must be embedded in legal and fiscal context. (The World Bank, 2000)

According to *'wind force 12'* (GWEC, 2005), by the end of year 2020, the total global installed capacity is estimated to be at 1,231 GW, over twenty times bigger than last year's, so that wind power electricity would account for 12% of overall global electricity. The blueprint of *'wind force 12'* indicates that wind power must be an integral part to resolve global energy problems. Wind power is not dispensable any longer. It becomes a rising industry with the great prospect for commercial development. It is reasonable to believe that wind power would be one of the most important alternative energy resources in the near future.

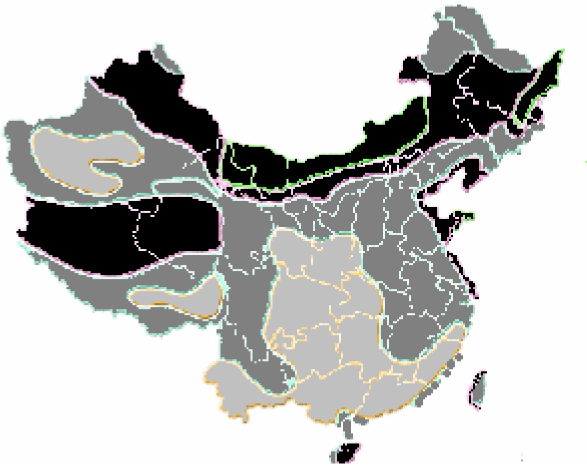
2.3 Wind power in China

With the large land mass and long coastline, China possesses world-class wind resources. An early meteorological data report (Xue, *et al*., 2001) recommended that the total exploitable on-shore wind capacity at 10 meters above the ground level in China is 253 GW. Recently, "the off-shore wind potential has been estimated at 750 GW" (Ku, *et al*., 2005), which would nearly double China's total energy generation capacity. In China, areas rich in wind power resources are mainly found in two areas: northern China's grasslands and Gobi desert, stretching from Inner Mongolia, Gansu, and Xinjiang provinces; and in the east coast from Shandong, Liaoling and the southeast coast in Fujian and Guangdong provinces (Feller, 2006). Wind resource in different regions in China is shown in Figure 2.2.

It was said that although China has huge exploitable wind potentialities and has been developing wind resources for over 15 years, the wind power output was only equivalent to that of some small coal-fired plants, in other words, the consumption of energy is less than one percent concerning wind power (Feller, 2006). The development of wind power in China is not only behind the developed countries but is also behind some developing countries, such as India. China's development of wind power started around the mid 80's. Over the past few years, wind power generation developed rapidly, with the installed capacity increasing from 224 MW in 1998 to 1,260 MW in 2005 (Zhang, *et al*., 2000; GWEC, 2006). By the end of 2005, the mainland had already built 59 wind plants with 1,854 wind turbine generators (Shi, 2006). In the late 2005, according to the government's "National Middle and Large Term Development Plan", the wind power target for 2010 is 5 GW, and for 2020 is 30GW (Feller, 2006).

Six years ago, there was such a surplus in electricity generation that the government did little to encourage wind power because wind costs were too high. Unfortunately, staring in 2003, China faced severe electricity shortages due to problematic coal, transport links, and water shortages. (Ku, *et al.,* 2005) Thereafter wind power has played a more important

Figure 2.2 *China's Wind Power Potential*



black = good, dark grey = ok, grey = poor

role in the electricity industry, but the high-cost is still the key barrier to restrain the expansion of wind power in China. Some studies show that the cost of coal-fired power is 50% lower than that of wind power in China. (Zhang and Zhao, 2006) Nowadays, the central and local governments are keeping an eye on the development of wind power. They are making great effort to lower its cost from multiple perspectives on technology, commerce and regulation. For example, they are making effort to develop and exploit more wind power through some mechanisms such as Build-Operate-Transfer (B.O.T.)[2] and Clean Development Mechanism (CDM)[3] to support electricity industry. All the facts above show that the development of Chinese wind power is just beginning and there is still a very long way ahead.

[2] According to Renewable Resource Development Center, the Build-Operate-Transfer (B.O.T.) project in China is defined as the project that only the eligible cooperation is permitted to have the exclusive right to develop wind power in the certain region.

[3] Clean Development Mechanism (CDM) is one of the Kyoto Protocol's flexibility mechanisms aimed at helping industrialized countries meet their greenhouse gas reduction targets. With this mechanism, China will construct more wind plants by obtaining financial assistance from some developed countries and realize both reduction of greenhouse gas and the development of wind power.

3 The basic model

Before we begin with the model, I would like to explain that as mentioned at the beginning of the Chapter 2, water resource is a renewable stock resource. The hydropower problem with the reservoir could therefore be taken as a dynamic problem because the water used to produce electricity today can alternatively be used tomorrow (Førsund, 2005). Unlike water resource, wind resource is a renewable flow resource. We do not have something like reservoirs to store the wind coming today and use it tomorrow although there may be residual wind coming today. In this study, thereby, the model is static one.

3.1 Necessary hypotheses for setting the models

Based on Zhu's report (2006), except for the eastern coastal areas summer (from June to August) is a scarcity season in the northern part of China. The model would be greatly simplified if we ignore the scarcity period during which the supply of wind power electricity is limited to a great extent, and may not meet the demand of wind power for lack of the available wind energy. It is reasonable to consider that the electricity producer would use other energy sources, such as coal, to generate electricity during this period.

In addition, due to the real status that the current installed capacity of wind power is much less than the potentially exploitable capacity of wind resource in China because of some limitations such as technology, the plant scales, etc., it is reasonable to suppose that the available wind resources are enough so that the producers could control how much they should use to produce electricity during any period T. Here T is different from t I used in Chapter 2. T is assumed to be any calendar year counted from January to December (removing scarcity months if necessary). Furthermore we assume that the technology for transferring wind to electricity is perfect which means the equal sign must be applied in the production function (2.3)

3.2 The objective function and constrains

Suppose there are only two kinds of electricity products in a specific region. One is wind power the other is coal-fired power. According to the microeconomic theory, utility can be thought of as a numeric measure of the total consumption of wind power and coal-fired power. The utility function during period T is:

$$U(e),\ U'(e) \geq 0,\ U''(e) \leq 0 \tag{3.1}$$

The utility function has standard properties of concavity. The marginal utility depends on the utility function that we use to reflect the consumers' willingness to pay to the total production of wind power and coal-fired power. Now, we measure the marginal utility, U', in money, and define the marginal utility as the marginal willingness to pay, p. The inverse demand function for electricity therefore is:

$$U'(e) = p(e) \tag{3.2}$$

where p will also be denoted as price of electricity in the following content. We assume that the price for electricity does not discriminate on whether the energy resources are renewable or not, in other words, the willingness to pay of wind power is just the same as that of coal-fired power.

From the government's point of view, we are interested in pursuing social optimum, in other words, concentrating on both consumer surplus and producer surplus. The demand curve would be shaped based on the demand function (3.2) above. On the other hand, we would use the marginal cost curve to measure plants' supply decision.

We will now introduce the cost function of wind power through the similar way adopted in Førsund (2005). In a real market, there must not be only one wind plant. Let us suppose that there are N wind plants in the market (Actually, according to Shi (2005), by the end of 2005, there are six wind plants constructed in Inner Mongolia region). The wind power production from a plant during period T is represented as e_i^{wind}, and each plant has an upper generation capacity, $\overline{e}_i^{wind}$ ($i = 1,2,...,N$). The upper generation capacity depends on the installation capacity and the amount of available wind resources. We know that the total costs can always be written as the sum of fixed costs and variable costs. In the case of wind power, the fixed component of the total annual cost is contributed by the initial investment, and the variable costs consist of the expenditure on operating and maintaining (Mathew, 2006). We do not give a specific cost function here in order to simplify the problem, and the marginal cost for wind power production is assumed to be constant, which means the rate of the change in costs for any change in output is constant. We can describe the cost function during period T as follows:

$$c_i^{wind} = c(e_i^{wind}), c_i^{'} = C, e_i^{wind} \leq \overline{e}_i^{wind}, i = 1,2,...,N \tag{3.3}$$

where C is a non-negative constant.

Our goal is to minimize the cost of producing a given level of the total output in this specific region:

$$\begin{aligned} & Min \sum_{i=1}^{N} c(e_i^{wind}) \\ & s.t. \\ & \sum_{i=1}^{N} e_i^{wind} \geq e^{wind}, e_i^{wind} \leq \overline{e}_i^{wind}, i = 1,2,...,N \end{aligned} \tag{3.4}$$

where e^{wind} is the given level of the total output in this region.

The Lagrangian is:

$$\begin{aligned} L = & -\sum_{i=1}^{N} c(e_i^{wind}) \\ & - \mu(-\sum_{i=1}^{N} e_i^{wind} + e^{wind}) \\ & - \sum_{i=1}^{N} \nu_i (e_i^{wind} - \overline{e}_i^{wind}), i = 1,2,...,N \end{aligned} \tag{3.5}$$

The Kuhn-Tucker conditions are:

$$\frac{\partial L}{\partial e_i^{wind}} = -c_i^{'} + \mu - \nu_i \leq 0 \perp e_i^{wind} \geq 0 \tag{3.6a}$$

$$\mu \geq 0(=0, if -\sum_{i=1}^{N} e_i^{wind} < -e^{wind}) \tag{3.6b}$$

$$\nu_i \geq 0(=0, if\ e_i^{wind} < \bar{e}_i^{wind}), i = 1,2,...,N \tag{3.6c}$$

It is not hard to find from conditions (3.6a) and (3.6c) that the producer i would produce nothing if the marginal cost for plant i is greater than the shadow price μ, i.e. if $c_i^{'} > \mu$, then $e_i^{wind} = 0$. Assuming for any given level of the total output, we get a set of plants producing positive output. For each of these plants, its production during period T must be positive, i.e. $e_i^{wind} > 0$. According to condition (3.6a), it yields:

$$c_i^{'} = \mu - \nu_i \tag{3.7}$$

To make sense of equality (3.7), μ must be greater than zero so that the first constraint for the problem (3.4) must be binding. Then it is not difficult to find that the optimal choice on allocating the outputs within these plants is that we rank these plants in order of increasing marginal cost, and make them reached their full capacity orderly. In other words, such plant will be ranked first to reach its full capacity that has the smallest marginal cost, which performs as merit order rank[4]. Thus the overall cost function approximately is:

$$c = c(e^{wind}), c' = C, e^{wind} \leq \sum_{i=1}^{N} \bar{e}_i^{wind} = \bar{e}^{wind} \tag{3.8}$$

where $\bar{e}^{wind}$ is the aggregate upper generation capacity for wind power.

The way for setting the cost function for coal-fired power is similar with what we just did for wind power. Assuming there are M coal-fired plants in this region, and each plant has

[4]merit order rank: according to dictionary of energy, in cases where multiple generation sources are available, generating facilities and individual generating units within those facilities are ranked according to their availability and the price that will be applied to the energy they produce. This ranking is referred to as merit order rank.

an upper capacity $\bar{e}_j^{coal}$ for generation e_j^{coal} $(j = 1,2,...,M)$, which only depends on the plant's scale. The cost of coal-fired power can also be described as the sum of fixed costs and variable costs. The variable costs of producing coal-fired power cling to the coal prices. The coal price may vary for some reasons such as the quality, the distance and consumers' demands on electricity. Similarly, we do not give a specific cost function here for simplification, and the marginal cost for coal-fired power production is assumed to be positive which means the cost increases as more coal-fired power electricity is produced. We describe the coal-fired power cost function as follows:

$$c_j = c(e_j^{coal}), c' > 0, e_j^{coal} \le \bar{e}_j^{coal}, j = 1,2,...,M \tag{3.9}$$

Our goal is still to minimize the cost of producing a given level of the total coal-fired power output in this region:

$$\begin{aligned} & Min\sum_{j=1}^{M} c(e_j^{coal}) \\ & s.t. \\ & \sum_{j=1}^{M} e_j^{coal} \ge e^{coal}, e_j^{coal} \le \bar{e}_j^{coal}, j = 1,2,...,M \end{aligned} \tag{3.10}$$

where e^{coal} is the given level of the total output.

Similarly, the overall cost function can be written as follows:

$$c = c(e^{coal}), c' > 0, c'' > 0, e^{coal} \le \sum_{j=1}^{M} \bar{e}_j^{coal} = \bar{e}^{coal} \tag{3.11}$$

where $\bar{e}^{coal}$ is aggregate upper generation capacity for coal-fired power.

Additionally, considering the environmental problem, the damage from using coal-fired power, $d(e^{coal})$, is can be regarded as an external cost which measures how environmental cost changes when coal-fired power output changes. However, to simplify our problem, we temporarily take $d(e^{coal})$ as zero in this study.

As mentioned before, we would pursue a social optimum, in other words, the objective function is to maximize the consumer surplus plus producer surplus. The objective function accordingly can be descried as follows:

$$Max \int_{x=0}^{e^{wind}+e^{coal}} p(x)dx - c(e^{wind}) - c(e^{coal}) \tag{3.12}$$

Let us now move to constraints. Firstly, we notice that if there is no MMS policy, only two constrains on production capacities should be involved in. One is that $e^{wind} \le \overline{e}^{wind}$, the other is $e^{coal} \le \overline{e}^{coal}$. However, in order to analyses MMS policy, besides the constraints on production capacities, another constraint should be added. For instance, the government would mandate a minimal absolute quantity of wind power production, W, in period T. This mandated target of wind power output, W, should be set within the interval of zero to wind power's upper generation capacity. The extra constraint, in mathematical terms, is $e^{wind} \ge W \quad (0 < W \le \overline{e}^{wind})$.

So far, we can describe the social planning problem without MMS policy as:

$$\begin{aligned} &Max \int_{x=0}^{e^{wind}+e^{coal}} p_n(x)dx - c(e^{wind}) - c(e^{coal}) \\ &s.t. \\ &e^{wind} \le \overline{e}^{wind}, e^{coal} \le \overline{e}^{coal} \end{aligned} \tag{3.13}$$

The lowercase n indicates that the problem we investigated is the one without MMS policy.

Lagrange function is:

$$\begin{aligned} L = &\int_{x=0}^{e^{wind}+e^{coal}} p_n(x)dx - c(e^{wind}) - c(e^{coal}) \\ &- \lambda_n(e^{wind} - \overline{e}^{wind}) \\ &- \gamma_n(e^{coal} - \overline{e}^{coal}) \end{aligned} \tag{3.14}$$

The first-order conditions are:

$$
\begin{aligned}
&\frac{\partial L}{\partial e^{wind}} = p_n(e^{wind} + e^{coal}) - c'(e^{wind}) - \lambda_n \le 0 \perp e^{wind} \ge 0 \\
&\frac{\partial L}{\partial e^{coal}} = p_n(e^{wind} + e^{coal}) - c'(e^{coal}) - \gamma_n \le 0 \perp e^{coal} \ge 0 \\
&\lambda_n \ge 0 \;\; (= 0 \;\; if \;\; e^{wind} < \overline{e}^{wind}) \\
&\gamma_n \ge 0 \;\; (= 0 \;\; if \;\; e^{coal} < \overline{e}^{coal})
\end{aligned}
\tag{3.15}
$$

where $c'(e^{wind})$ is equal to a non-negative constant C for short below.

Then the social planning problem with MMS policy can be described as:

$$
\begin{aligned}
&Max \int_{x=0}^{e^{wind}+e^{coal}} p(x)dx - c(e^{wind}) - c(e^{coal}) \\
&s.t. \\
&e^{wind} \le \overline{e}^{wind}, e^{wind} \ge W, e^{coal} \le \overline{e}^{coal}
\end{aligned}
\tag{3.16}
$$

where $0 < W \le \overline{e}^{wind}$.

Lagrange function is:

$$
\begin{aligned}
L = &\int_{x=0}^{e^{wind}+e^{coal}} p(x)dx - c(e^{wind}) - c(e^{coal}) \\
&- \lambda(e^{wind} - \overline{e}^{wind}) \\
&- \gamma(e^{coal} - \overline{e}^{coal}) \\
&- \beta(-e^{wind} + W), \;\; 0 < W \le \overline{e}^{wind}
\end{aligned}
\tag{3.17}
$$

The first-order conditions are:

$$
\begin{aligned}
&\frac{\partial L}{\partial e^{wind}} = p(e^{wind} + e^{coal}) - c'(e^{wind}) - \lambda + \beta \le 0 \perp e^{wind} \ge 0 \\
&\frac{\partial L}{\partial e^{coal}} = p(e^{wind} + e^{coal}) - c'(e^{coal}) - \gamma \le 0 \perp e^{coal} \ge 0 \\
&\lambda \ge 0 \;\; (= 0 \;\; if \;\; e^{wind} < \overline{e}^{wind}) \\
&\gamma \ge 0 \;\; (= 0 \;\; if \;\; e^{coal} < \overline{e}^{coal}) \\
&\beta \ge 0 \;\; (= 0 \;\; if \;\; e^{wind} > W)
\end{aligned}
\tag{3.18}
$$

4 Welfare comparison for the scenarios with or without MMS

In Chapter 3, we constructed the welfare-maximizing model by mixing wind power with coal-fired power. Here we continue that investigation thought the welfare analysis for the scenarios with or without MMS policy. In order to be close to the current power market, there is an important assumption which is applicable to both the scenarios with or without MMS policy: the output of coal-fired power is always positive, mathematically, $e^{coal} > 0$.

4.1 The first comparison

Based on our assumptions, for the scenario without MMS policy, we can rewrite the conditions of (3.15) as:

$$\begin{aligned}
&p_n(e^{wind} + e^{coal}) - c'(e^{wind}) - \lambda_n \le 0 \perp e^{wind} \ge 0 \\
&p_n(e^{wind} + e^{coal}) - c'(e^{coal}) - \gamma_n = 0 \\
&\lambda_n \ge 0 \ \ (= 0 \ \ if \ \ e^{wind} < \bar{e}^{wind}) \\
&\gamma_n \ge 0 \ \ (= 0 \ \ if \ \ e^{coal} < \bar{e}^{coal})
\end{aligned} \tag{4.1}$$

According to conditions of (4.1), we notice that there will be two possible situations existing in the market. One is that wind power will not be used in the situation where:

$$p_n = c'(e^{coal}) + \gamma_n < c'(e^{wind}) \tag{4.2}$$

If the market price is less than the value of wind power's marginal cost, the wind power will not be used, in other words, only coal-fired electricity exists in the market.

The other possibility is that both wind power and coal-fired power are used in the situation where:

$$\begin{aligned}
&p_n = c'(e^{wind}) + \lambda_n = c'(e^{coal}) + \gamma_n \\
&\lambda_n \ge 0 \ \ (= 0 \ \ if \ \ e^{wind} < \bar{e}^{wind}) \\
&\gamma_n \ge 0 \ \ (= 0 \ \ if \ \ e^{coal} < \bar{e}^{coal})
\end{aligned} \tag{4.3}$$

However, referring to the scenario with MMS policy, we notice that besides our previous assumption, $e^{coal} > 0$, the output of wind power must also be positive, i.e. $e^{wind} > 0$ because of the introduction of MMS policy, i.e. $e^{wind} \geq W$ ($0 < W \leq \bar{e}^{wind}$). We say that there is only one possible situation in the market, that is, wind power will coexist with coal-fired power. Accordingly, conditions of (3.18) could be rearranged as follows:

$$
\begin{aligned}
&p(e^{wind} + e^{coal}) = c'(e^{wind}) + \lambda - \beta \\
&p(e^{wind} + e^{coal}) = c'(e^{coal}) + \gamma \\
&\lambda \geq 0 \;\; (= 0 \;\; if \;\; e^{wind} < \bar{e}^{wind}) \\
&\gamma \geq 0 \;\; (= 0 \;\; if \;\; e^{coal} < \bar{e}^{coal}) \\
&\beta \geq 0 \;\; (= 0 \;\; if \;\; e^{wind} > W)
\end{aligned}
\tag{4.4}
$$

4.2 The second comparison

4.2.1 The eight cases

Note that, the conditions of (4.4) may fall into eight cases according to the different combination of shadow prices' notation. In this section, we will make the following eight comparisons to explain further why we need MMS policy. In order to make the comparisons easier, when we consider the scenario without MMS policy, we will only consider the possibility that wind power is used in the market. Moreover, to simplify the problems, we would only discuss the situation where the solutions exist. We now start the systematic procedure:

Case I $\lambda_n = 0,\;\; \gamma_n = 0$ (without MMS), versus, $\lambda = 0,\;\; \gamma = 0 \;\; and\, \beta > 0$ (with MMS)

First, look at the scenario without MMS. Rearranging conditions of (4.3), yields:

$$
\begin{aligned}
&p_n = c'(e^{wind}) = c'(e^{coal}) \\
&e^{wind} \leq \bar{e}^{wind}, e^{coal} \leq \bar{e}^{coal}
\end{aligned}
\tag{4.5a}
$$

Note that, from the first condition of (4.5a), the two marginal cost curves intersect at the optimal allocation point. Suppose that the demand curve, the coal-fired's marginal cost curve, and the upper generation capacities are given. In Figure 4.1(a), they are depicted by solid lines. Then according to the conditions of (4.5a), the wind's marginal cost curve shaped as in Figure 4.1(a). Note that the value of the market price is determined by the shape of the wind's marginal cost curve. The market price would therefore be set within a closed interval $[p_{n1}, p_{n2}]$. At the p_{n1} level, the full capacity of wind power will be reached. Outputs of coal-fired power and wind power are respectively e_1^{coal} and $\bar{e}^{wind}$. At the p_{n2} level, the full capacity of coal-fired power will be reached, the outputs of coal-fired power and wind power are respectively $\bar{e}^{coal}$ and e_2^{wind}.

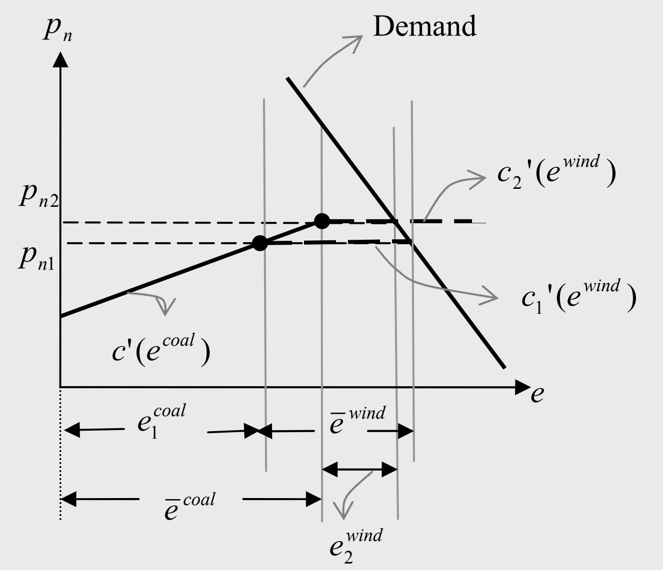


Figure 4.1(a) *Social optima for the scenario with* $\lambda_n = 0, \quad \gamma_n = 0$

Now move to the scenario with MMS. We have that $W = e^{wind} \le \bar{e}^{wind}$ and $e^{coal} \le \bar{e}^{coal}$. The former item indicates the wind output, in the market, is just equal to the mandated target, W. There is no extra wind power output in the market. The latter one says the coal-fired output is either equal to upper capacity or less than it. Rearranging the conditions of (4.4), yields:

$$p(e^{wind} + e^{coal}) = c'(e^{wind}) - \beta \Rightarrow p < c'(e^{wind})$$
$$p(e^{wind} + e^{coal}) = c'(e^{coal}) \tag{4.5b}$$

From (4.5b) we learn that although the market price is less than the marginal cost of wind power at the optimal allocation point, the wind power exists in the market because of the MMS policy. However, we also note that in order to make MMS policy possible, we must provide some supporting measures to support MMS policy. The governmental subsidy could be one of those supporting measures. For example, the government should let the amount of the subsidy at least equal β. We can depict this scenario in Figure 4.1(b). Taking demand curve, two marginal cost curves and two upper generation capacities given, the market price would be set according to the value of W. With a smaller target of wind power output, W_1, the market decides the price at p_1 level. At the same time, the full capacity of coal-fired power will be reached. With a larger target of wind power output, such as the full capacity W_2, the market price would be set at p_2 level. At the same time, the contribution from coal-fired power is e_2^{coal}, and from wind power is W_2. The supporting measure β_2 is stronger than β_1.

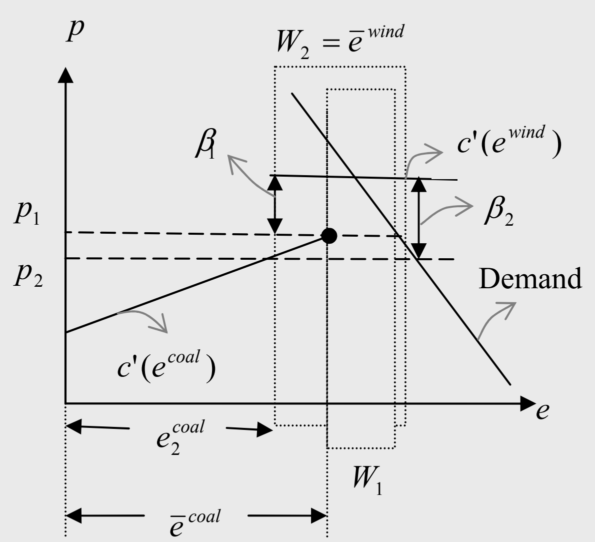


Figure 4.1(b) *Social optima for the scenario with* $\lambda = \gamma = 0, \beta > 0$

From Figure 4.1(b), we also notice that if W, the target of wind power output, is big enough (in this case, $W_1 < W < W_2$), then the full capacity of coal-fired power will not be reached. In other words, the overall electricity demand is satisfied whilst the utilization of coal-fired power is limited to some extent, which contributes to a better environment.

Comparing Figure 4.1(b) with Figure 4.1(a), if we adopt the same demand curve, the coal-fired's marginal cost curve, and the upper capacity vertical lines in both the scenarios with and without MMS, although the shapes of wind's marginal cost curves are different, the market price and the outputs allocation in the scenario with MMS could also be the same as those in the scenario without MMS, as long as the target value is set within a proper interval. Of course, the advantage of performing MMS policy, in this case, is that the target output of wind power, W, could be realized even under the circumstance that the level of wind power's marginal cost is higher than the market price at the optimal allocation point.

Case II $\lambda_n = 0, \gamma_n = 0$ (without MMS), versus, $\lambda = 0, \gamma = 0$ *and* $\beta = 0$ (with MMS)

For the scenario with MMS, we accordingly have that $W \le e^{wind} \le \bar{e}^{wind}$ and $e^{coal} \le \bar{e}^{coal}$. From the former item we know that wind power output is at least as much as the mandated target. Rearranging the conditions of (4.4), yields:

$$p(e^{wind} + e^{coal}) = c'(e^{wind}) = c'(e^{coal}) \tag{4.6}$$

We notice that the condition of (4.6) is similar with the one in the scenario without MMS discussed in Case I (see conditions of 4.5(a)). It is not hard to conclude that as long as all five curves and vertical lines in the scenario without MMS are the same as those in the scenario with MMS, the optimal solutions in these two scenarios must be the same as well, no matter we perform MMS policy or not.

Case III $\lambda_n = 0, \gamma_n > 0$ (without MMS), versus, $\lambda = 0, \gamma > 0$ *and* $\beta > 0$ (with MMS)

Look at the scenario without MMS firstly. Rearranging conditions of (4.3), yields:

$$\begin{aligned} & p_n = c'(e^{wind}) \\ & p_n = c'(e^{coal}) + \gamma_n \Rightarrow p_n > c'(e^{coal}) \\ & e^{wind} \le \bar{e}^{wind}, e^{coal} = \bar{e}^{coal} \end{aligned} \tag{4.7a}$$

Suppose that the demand curve, the coal-fired's marginal cost curve, and the upper capacity vertical lines are given as depicted in Figure 4.2(a). Since the coal-fired's upper capacity is reached, the market price would be set within an open interval (p_{n1}, p_{n2}), where the value of p_{n1} is equal to the coal-fired's marginal cost at its full capacity point, and the value of p_{n2} is set when the demand curve intersect with coal-fired's full capacity vertical line. If the wind's marginal cost curve would shape as in Figure 4.2(a), the market price would be set at p_n level, and the outputs for coal-fired power and wind power are, respectively, $\bar{e}^{coal}$ and e_n^{wind}.

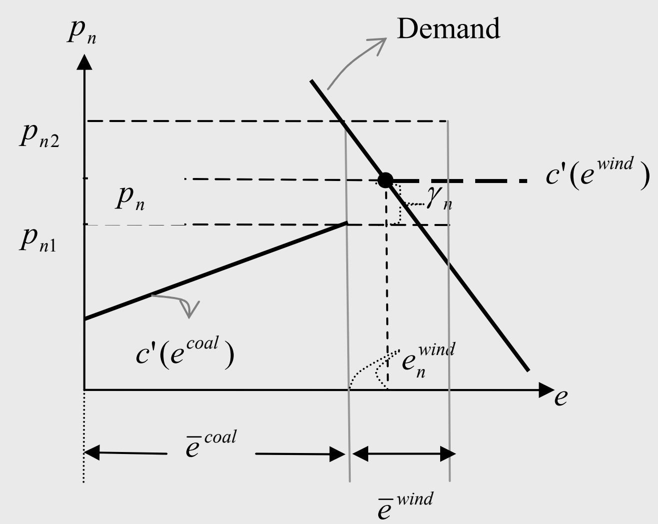


Figure 4.2(a) *Social optima for the scenario with* $\lambda_n = 0, \ \gamma_n > 0$

We now move to the scenario with MMS. We have that $W = e^{wind} \le \bar{e}^{wind}$ and

$e^{coal} = \bar{e}^{coal}$, which indicate that wind power output is just equal to the mandated target and coal-fired power output is at full capacity level. Rearranging the conditions of (4.4), yields:

$$\begin{aligned} p(e^{wind} + e^{coal}) &= c'(e^{wind}) - \beta \Rightarrow p < c'(e^{wind}) \\ p(e^{wind} + e^{coal}) &= c'(e^{coal}) + \gamma \Rightarrow p > c'(e^{coal}) \end{aligned} \tag{4.7b}$$

In this case, the demand curve, the two marginal cost curves, and the two upper capacity vertical lines are given as depicted in Figure 4.2(b). Then the market price would be set according to the target value of W. Since the coal-fired's full capacity reached, the market price must be greater than p_0. It will be set in accordance with the target of wind power output. Keeping all other conditions fixed, with a smaller target of wind power outputs, W_1, the market would set the price at p_1 level. At the same time the shadow price on coal resource is at γ_1 level. With a larger target of wind power outputs, W_2, the market price would be set at p_2 level whilst the shadow price of coal resource is at γ_2 level. Apparently, a larger target brings more clean electricity.

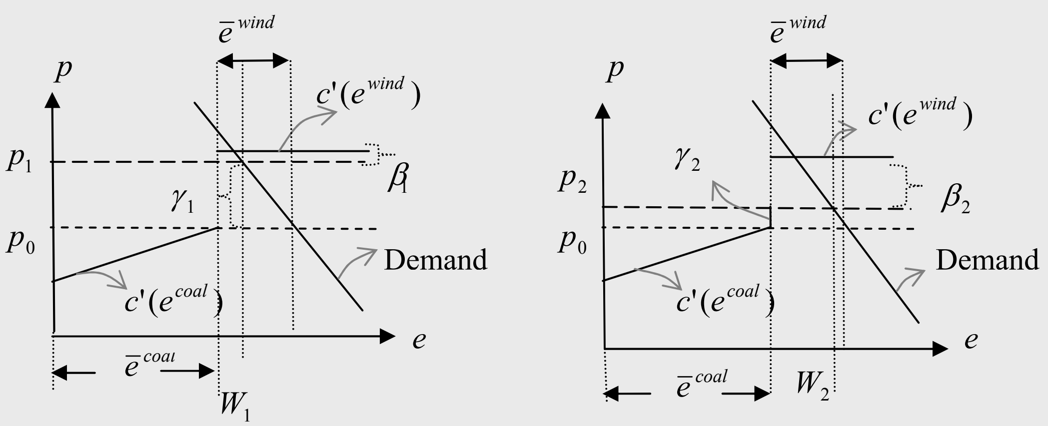


Figure 4.2(b) *Social optima for the scenario with* $\lambda = 0, \gamma > 0, \beta > 0$

From (4.7b) we also know that MMS policy with necessary supporting measures make wind power existed in the market although the market price is less than wind power's marginal cost at the optimal allocation point.

Figure 4.3 is trying to compare optimum for the scenario without MMS with the scenario with MMS by giving the same demand curve, marginal cost curves and upper capacity vertical lines. It is not difficult to see that with MMS, at the optimal allocation point, wind power electricity is equal to the target W and the market price is at p level; without MMS, at the optimal allocation point, wind power electricity is only e_n^{wind} and the market price is at p_n level, where e_n^{wind} is less than W and p_n is higher than p. Then we conclude that in this case, MMS policy performs well on producing wind power.

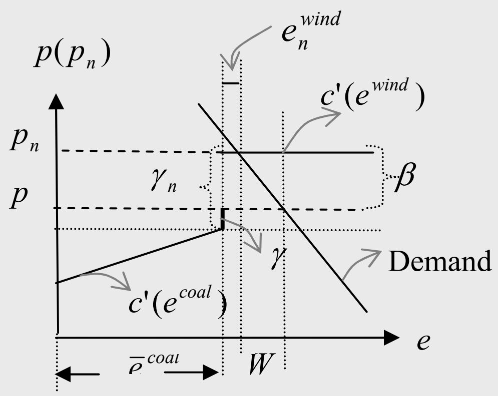


Figure 4.3 *Comparison the social optimum for the scenario with MMS policy where* $\lambda = 0, \quad \gamma > 0, \beta > 0$ *with that for the scenario without MMS policy where* $\lambda_n = 0, \gamma_n > 0$

<u>Case IV</u> $\lambda_n = 0, \gamma_n > 0$ (without MMS), versus, $\lambda = 0, \gamma > 0$ *and* $\beta = 0$ (with MMS)

For the scenario with MMS, we accordingly have that $W \le e^{wind} \le \bar{e}^{wind}$ and $e^{coal} = \bar{e}^{coal}$. From the former item we know that wind power output is at least as much as the mandated target. The latter item shows that the coal-fired's full capacity must be reached. Rearranging the conditions of (4.4), yields:

$$\begin{aligned} &p = c'(e^{wind}) \\ &p = c'(e^{coal}) + \gamma \Rightarrow p > c'(e^{coal}) \end{aligned} \tag{4.8}$$

It is easy to see that the conditions of (4.8) are similar with the first two conditions of (4.7a). Therefore, we conclude that as long as all other conditions are the same, there is no improvement even if we perform MMS policy.

<u>Case V</u> $\lambda_n > 0$, $\gamma_n = 0$ (without MMS), versus, $\lambda > 0$, $\gamma = 0$, $\beta > 0$ (with MMS)

We firstly discuss the scenario without MMS. Note that $e^{wind} = \bar{e}^{wind}, e^{coal} \le \bar{e}^{coal}$. The full capacity of wind power must be reached. Rearranging the conditions of (4.3) yields

$$\begin{aligned} &p_n = c'(e^{wind}) + \delta \Rightarrow p_n > c'(e^{wind}) \\ &p_n = c'(e^{coal}) \end{aligned} \tag{4.9a}$$

From (4.9a), we know that at the optimal allocation point, the market price is equal to the marginal cost of coal-fired power but greater than the marginal cost of wind power.

Moving to the scenario with MMS, we have the facts that $e^{wind} = W = \bar{e}^{wind}$ and $e^{coal} \le \bar{e}^{coal}$. The first item indicates that the mandated target of wind power must be set at its full capacity level and the target must be accomplished. From the second item we say that keeping two full capacities and the coal-fired power's marginal cost curve fixed, whether the coal-fired power output is less than full capacity or as much as full capacity depending on what the overall demand curve looks like. Rearranging the conditions of (4.4), yields:

$$\begin{aligned} &p = c'(e^{wind}) + \lambda - \beta \\ &p = c'(e^{coal}) \end{aligned} \tag{4.9b}$$

From (4.9b) we know that at the optimal allocation point, the market price would be equal to the coal-fired's marginal cost, but the relationship between the market price and the wind's marginal cost depends on the values of λ and β. In both figure 4.4(a) and figure 4.4(b), at the optimal allocation point, the wind's marginal cost is depicted as curve

$c_1'(e^{wind})$, which is lower than the market price if λ is greater than β; looks like curve $c_2'(e^{wind})$, which is equal to the market price if λ is equal to β; and is depicted as curve $c_3'(e^{wind})$, which is higher than the market price if λ is less than β. In the third situation, the supporting measure has to be set. According to the different shapes of the demand curves, the coal-fired full capacity would not be reached in figure 4.4(a) but realized in figure 4.4(b)

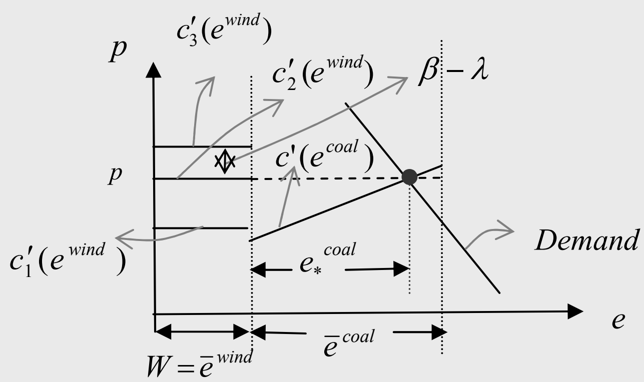


Figure 4.4(a) *Social optima of the scenario with* $\lambda > 0, \gamma = 0$ *and* $\beta > 0$ *where the full capacity of coal-fired power is not*

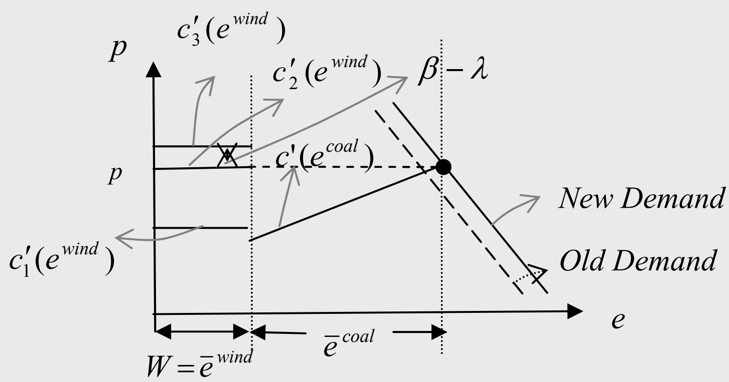


Figure 4.4(b) *Social optima of the scenario with* $\lambda > 0, \gamma = 0$ *and* $\beta > 0$ *where the full capacity of coal-fired power is reached.*

Comparing the scenario without MMS with the scenario with MMS, in this case, we conclude the wind power's marginal cost curve can not be depicted as curve $c_2'(e^{wind})$ or $c_3'(e^{wind})$ if there is no MMS policy.

<u>Case VI</u> $\lambda_n > 0, \gamma_n = 0$ (without MMS), versus, $\lambda > 0, \gamma = 0$ *and* $\beta = 0$ (with MMS)

With MMS policy, we accordingly have that $W \le e^{wind} = \bar{e}^{wind}$ and $e^{coal} \le \bar{e}^{coal}$. From the first item we know that the full capacity of wind power will be reached which indicates that the mandated target is undoubtedly accomplished. The second item has the same explanation as that in Case V. Rearranging conditions of (4.4), yields:

$$\begin{aligned} &p = c'(e^{wind}) + \lambda \Rightarrow p > c'(e^{wind}) \\ &p = c'(e^{coal}) \end{aligned} \qquad (4.10)$$

Comparing the conditions of (4.10) with the ones of (4.9a), it is easy to conclude that whether MMS policy exists or not, the wind's full capacity must be reached. Keeping demand curve, two marginal curves, and vertical lines are the same in these two scenarios, MMS policy does not affect the social optimal solutions. We illustrate one possibility in Figure 4.5, where optimal outputs for wind power and coal-fired power are, respectively, $\bar{e}^{wind}$ and e_*^{coal}.

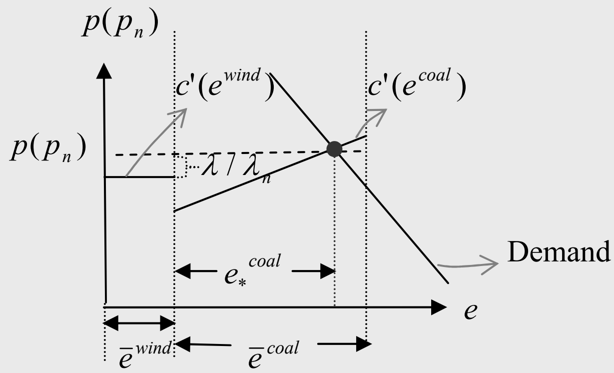


Figure 4.5 *Social optima for the scenario with* $\lambda > 0, \gamma = 0, \beta = 0$ *and the scenario with* $\lambda_n > 0$, $\gamma_n = 0$

Case VII $\lambda_n > 0, \gamma_n > 0$ (without MMS), versus, $\lambda > 0, \gamma > 0, \ \beta > 0$ (with MMS)

In this case, for the scenario without MMS, we have that:

$e^{wind} = \overline{e}^{wind}, e^{coal} = \overline{e}^{coal}$

$$\begin{aligned} p_n &= c'(e^{wind}) + \lambda_n \Rightarrow p_n > c'(e^{wind}) \\ p_n &= c'(e^{coal}) + \gamma_n \Rightarrow p_n > c'(e^{coal}) \end{aligned} \tag{4.11a}$$

where both outputs are at the full capacity level. At the optimal allocation point, no matter what the values of the two marginal costs are, the market price should be higher than the bigger one.

Turning to scenario with MMS, we have the facts that $e^{wind} = W = \overline{e}^{wind}$ and $e^{coal} = \overline{e}^{coal}$. Note that the mandated target must be set at the wind's full capacity level, and coal-fired's full capacity is also reached. Rearranging the conditions of (4.4), yields:

$$\begin{aligned} p &= c'(e^{wind}) + \lambda - \beta \\ p &= c'(e^{coal}) + \gamma \Rightarrow p > c'(e^{coal}) \end{aligned} \tag{4.11b}$$

From (4.11b) we know that at the optimal allocation point, the market price must be higher than the coal-fired's marginal cost but the relationship between the market price and the wind's marginal cost depends on the values of λ and β. Unlike the scenario without MMS, in this scenario with MMS, the wind's marginal cost can be depicted as in Figure 4.6. It may shape as curve $c_1'(e^{wind})$, which is lower than the market price if λ is greater than β; like curve $c_2'(e^{wind})$, which is equal to the market price if λ is equal to β; and as curve $c_3'(e^{wind})$, which is higher than the market price if λ is less than β. In the third situation, the supporting measure has to be considered.

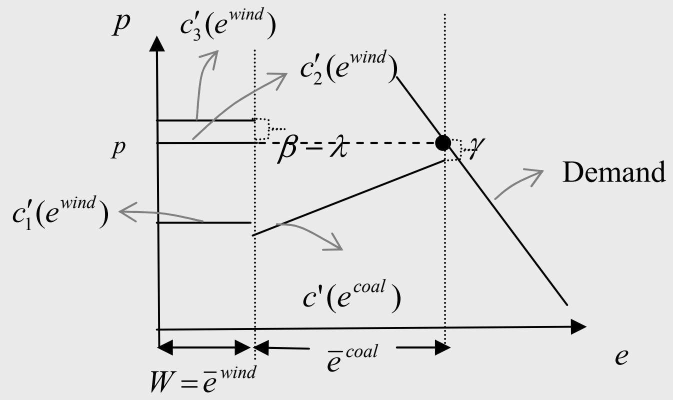


Figure 4.6 *Social optima of the scenario with $\lambda > 0, \gamma > 0$ and $\beta > 0$ where both full capacities are reached.*

Case VIII $\lambda_n > 0, \gamma_n > 0$ (without MMS), versus, $\lambda > 0, \gamma > 0$ *and* $\beta = 0$ (with MMS)

In this case, for the scenario with MMS, we accordingly have that $W \le e^{wind} = \bar{e}^{wind}$ and $e^{coal} = \bar{e}^{coal}$. They show that the both wind power and coal-fired power's full capacities are reached. Rearranging the conditions of (4.4), yields:

$$\begin{aligned} p = c'(e^{wind}) + \lambda \Rightarrow p > c'(e^{wind}) \\ p = c'(e^{coal}) + \gamma \Rightarrow p > c'(e^{coal}) \end{aligned} \tag{4.12}$$

From (4.12) we know that at the optimal allocation point, no matter what values of these two marginal costs are, the market price should be higher than the bigger value of these two marginal costs. At the same time, both kinds of powers' full capacities would be reached. This status in real life can similarly be understood as the overall demand exceeds overall supply for electricity.

Comparing conditions of (4.12) with ones of (4.11a), it is intuitively clear that in this case, suppose demand curve, marginal cost curves, and full capacity vertical lines are given, no matter we perform MMS policy or not, the optimal solutions are the same. The Figure 4.7

gives an example with the situation where $c'(\bar{e}^{wind}) > c'(\bar{e}^{coal})$ at the optimal allocation point.

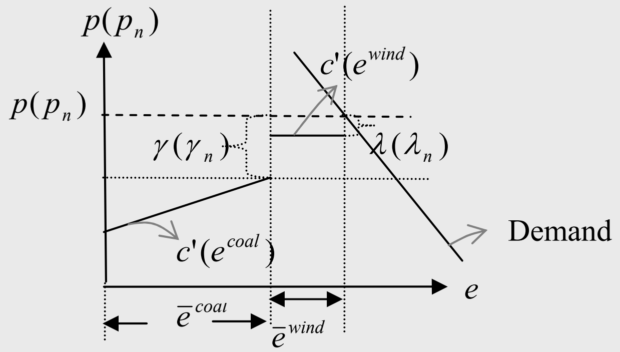


Figure 4.7 *Social optima for the scenario with* $\lambda > 0, \gamma > 0, \beta = 0$ *and the scenario with* $\lambda_n > 0$, $\gamma_n > 0$

4.2.2 With a zero marginal cost on wind power

In real life the marginal cost on wind power are not zero, but for our purposes it is helpful to investigate the mixed system with a zero marginal cost, since we can then know in what situations MMS policy can function. Moreover, the case of zero marginal cost assumption can approximately be understood as CDM where almost all initial costs for wind power are granted by some industrial countries whilst variable costs can approximately be taken as zero because the fuel-wind-is free. Similarly, we investigate the social optimization problem without MMS firstly. Therefore the problem can be described by slightly altering the problem (3.13) as follows:

$$
\begin{aligned}
&Max \int_{x=0}^{e^{wind}+e^{coal}} p_n(x)dx - c(e^{coal}) \\
&s.t. \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (4.13) \\
&e^{wind} \le \bar{e}^{wind}, e^{coal} \le \bar{e}^{coal}
\end{aligned}
$$

Lagrange function is:

$$
\begin{aligned}
L = & \int_{x=0}^{e^{wind}+e^{coal}} p_n(x)dx - c(e^{coal}) \\
& -\lambda_n(e^{wind} - \overline{e}^{wind}) \\
& -\gamma_n(e^{coal} - \overline{e}^{coal})
\end{aligned} \tag{4.14}
$$

The first-conditions are:

$$
\begin{aligned}
& \frac{\partial L}{\partial e^{wind}} = p_n(e^{wind} + e^{coal}) - \lambda_n \le 0 \perp e^{wind} \ge 0 \\
& \frac{\partial L}{\partial e^{coal}} = p_n(e^{wind} + e^{coal}) - c'(e^{coal}) - \gamma_n \le 0 \perp e^{coal} \ge 0 \\
& \lambda_n \ge 0 \ \ (= 0 \ \ if \ \ e^{wind} < \overline{e}^{wind}) \\
& \gamma_n \ge 0 \ \ (= 0 \ \ if \ \ e^{coal} < \overline{e}^{coal})
\end{aligned} \tag{4.15}
$$

It is reasonable to suppose the market price is positive. From conditions of (4.15), λ_n must be positive, the full capacity of wind power therefore must be reached. It is easy to understand that wind power could priorly be used since there is no cost, and coal-fired power will participate only if wind power's full capacity is reached. Based on the discussion above, we notice that the coal-fired power would face a residual demand curve and how much the coal-fired power produced depends on the residual demand curve. Then the total consumption of electricity is $\overline{e}^{wind}$ plus e_*^{coal}. In Figure 4.8, panel A, the heavy line is the overall demand curve. Since the full capacity of wind power, $\overline{e}^{wind}$, will priorly be reached, the demand curve faced by coal-fired power then would parallel shift left by $\overline{e}^{wind}$. Since the full capacity of coal-fired power is much greater than that of wind power, the contribution from coal-fired power would be determined by the residual demand curve together with coal-fired's marginal cost curve as depicted as in panel B.

Based on the analyses above, it is easy to conclude that the optimal problem could be solved whilst the wind power have been used maximally without MMS policy. In other words, the MMS policy would be redundant in the CDM case. Of course, the CDM project is significantly beneficial to the development of wind power, and worthy to be developed greatly.

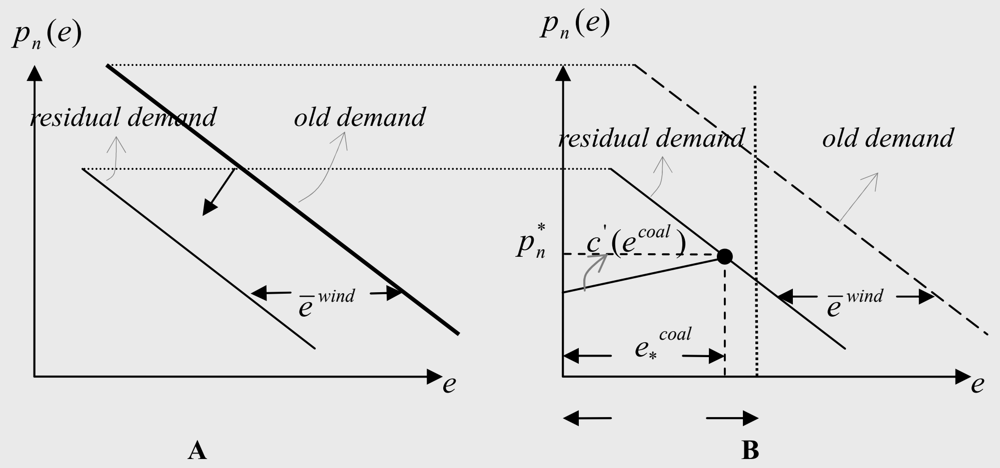


Figure 4.8 *In panel A, the full capacity curve of wind power and the overall demand curve determine that the demand curve for coal-fired power would shift inward of the overall demand curve; in panel B, the residual demand curve and the marginal cost curve for coal-fired power determine the optimal market price and the contribution from coal-fired power.*

4.2.3 A brief summing up

From previous analyses, we know that without MMS policy, the wind power would be used in the market only if the market price is greater or equal to the wind power's marginal cost at the optimal allocation point. In Case I, III, V and VII, the performance of MMS policy might make a positive wind power output possible even if the marginal cost of wind power may higher than the market price at the optimal allocation point. However, this does not mean that a positive target of wind power must take place without any supporting measures. Therefore, we say that assist in implementing the MMS, supporting measures are necessarily required. In Case II, IV, VI, the MMS policy does not have remarkable functions any more in the market where the level of market price is greater or equal to the wind's marginal cost at the optimal allocation point. In Case VIII and CDM case, the excess of electricity demand and a zero marginal cost on wind power respectively make MMS policy seem like redundant.

5 Market organization

In the preceding chapters we have analyzed the consequences by introducing MMS policy in the social planning model. In this chapter we turn to investigate MMS policy in two different market organizations, a competitive market and a monopoly market. In this chapter, we continue to suppose there are only wind power electricity and coal-fired power electricity in the market, and the output of coal-fired power is always positive, i.e. $e^{coal} > 0$. Moreover, the market price does not discriminate on the energy resources.

5.1 Free competition with MMS

Consider a competitive industry that there are a number of small plants to supply either wind power electricity or coal-fired electricity. Recalling the process of constructing cost functions in Chapter 3, it is nature to think the behavior of these suppliers is similar. Therefore, it is reasonable to treat all small wind power suppliers as an aggregate unit to simplify the problem. Also we would treat all suppliers of coal-fired power as another aggregate unit. In other words, there are only one wind power supplier and one coal-fired power supplier existing in this market. Then we continue to use the cost functions as we constructed in Chapter 3. Assume that there is no uncertainty, so the market price p is known.

We now introduce MMS policy in this market. Therefore, the profit maximization problem of wind power producer is:

$$\begin{aligned}
&Max \quad p \cdot e^{wind} - c(e^{wind}) \\
&s.t. \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (5.1) \\
&e^{wind} \le \bar{e}^{wind}, e^{wind} \ge W (0 < W \le \bar{e}^{wind})
\end{aligned}$$

Lagrange function is:

$$\begin{aligned}L &= p \cdot e^{wind} - c(e^{wind}) \\ &- \lambda(e^{wind} - \bar{e}^{wind}) \\ &+ \beta(-e^{wind} + W), (0 < W \leq \bar{e}^{wind})\end{aligned} \tag{5.2}$$

The first-order conditions are:

$$\begin{aligned}&\frac{\partial L}{\partial e^{wind}} = p - c'(e^{wind}) - \lambda + \beta \leq 0 \perp e^{wiind} \geq 0 \\ &\lambda \geq 0 \quad (= 0 \quad if \quad e^{wind} < \bar{e}^{wind}) \\ &\beta \geq 0 \quad (= 0 \quad if \quad e^{wind} > W)\end{aligned} \tag{5.3}$$

Note that the output of wind power must be positive due to the introduction of MMS policy in this model, i.e. $e^{wind} > 0$. We can rewrite the conditions of (5.3) as:

$$\begin{aligned}&p = c'(e^{wind}) + \lambda - \beta \\ &\lambda \geq 0 \quad (= 0 \quad if \quad e^{wind} < \bar{e}^{wind}) \\ &\beta \geq 0 \quad (= 0 \quad if \quad e^{wind} > W)\end{aligned} \tag{5.4}$$

Now, we move to the profit maximization problem of coal-fired power producer.

$$\begin{aligned}&Max \quad p \cdot e^{coal} - c(e^{coal}) \\ &s.t. \\ &e^{coal} \leq \bar{e}^{coal}\end{aligned} \tag{5.5}$$

Lagrange function is:

$$\begin{aligned}L &= p \cdot e^{coal} - c(e^{coal}) \\ &- \gamma(e^{coal} - \bar{e}^{coal})\end{aligned} \tag{5.6}$$

The first-order conditions are:

$$\begin{aligned}&\frac{\partial L}{\partial e^{coal}} = p - c'(e^{coal}) - \gamma \leq 0 \perp e^{coal} \geq 0 \\ &\gamma \geq 0 \quad (= 0 \quad if \quad e^{coal} < \bar{e}^{coal})\end{aligned} \tag{5.7}$$

Taking account of our assumption, $e^{coal} > 0$,the conditions of (5.7) can be rewritten as:

$$\begin{aligned}&p = c'(e^{coal}) + \gamma \\ &\gamma \geq 0 \quad (= 0 \quad if \quad e^{coal} < \bar{e}^{coal})\end{aligned} \tag{5.8}$$

Combining conditions of (5.4) with conditions of (5.8), since the market price does not discriminate on energy resources and could be regarded as given, it is nature to have:

$$\begin{aligned} & p = c'(e^{wind}) + \lambda - \beta = c'(e^{coal}) + \gamma \\ & \lambda \geq 0 \;\; (= 0 \;\; if \;\; e^{wind} < \overline{e}^{wind}) \\ & \beta \geq 0 \;\; (= 0 \;\; if \;\; e^{wind} > W) \\ & \gamma \geq 0 \;\; (= 0 \;\; if \;\; e^{coal} < \overline{e}^{coal}) \end{aligned} \tag{5.9}$$

Comparing the private conditions of (5.9) with the social conditions of (4.4) we have that if the marginal cost curves, the level of full capacities and the overall demand curve faced by the producers are the same as those in the social planning problem, then a competitive market will sustain the social solutions.

5.2 Monopoly with MMS

Suppose that the consumers are indifferent between wind power electricity and coal-fired power electricity. We now turn to the case by considering the monopolist as a single production unit to produce either coal-fired power or wind power electricity. Similarly, the cost functions we constructed in Chapter 3 are also applied to this market. In current Chinese power market, the grid company can approximately be regarded as a monopolist who chooses the price to sell either coal-fired power or wind power output to consumers so that maximize its overall profits. We assume that the monopolist faces the demand function $p = p(e), e = e^{wind} + e^{coal}$. The optimization problem of the monopolist with MMS policy is:

$$\begin{aligned} & Max \;\; p(e) \cdot e - c(e^{wind}) - c(e^{coal}) \\ & s.t. \\ & e = e^{wind} + e^{coal}, e^{wind} \leq \overline{e}^{wind}, e^{coal} \leq \overline{e}^{coal}, e^{wind} \geq W \end{aligned} \tag{5.10}$$

where $0 < W \leq \overline{e}^{wind}$

Lagrange function is:

$$
\begin{aligned}
L = {} & p(e^{wind} + e^{coal}) \cdot (e^{wind} + e^{coal}) - c(e^{wind}) - c(e^{coal}) \\
& - \lambda(e^{wind} - \bar{e}^{wind}) \\
& - \gamma(e^{coal} - \bar{e}^{coal}) \\
& + \beta(-e^{wind} + W)
\end{aligned} \tag{5.11}
$$

The first-order conditions are:

$$
\begin{aligned}
& \frac{\partial L}{\partial e^{wind}} = p + p' \cdot (e^{wind} + e^{coal}) - c'(e^{wind}) - \lambda + \beta \le 0 \perp e^{wind} \ge 0 \\
& \frac{\partial L}{\partial e^{coal}} = p + p' \cdot (e^{wind} + e^{coal}) - c'(e^{coal}) - \gamma \le 0 \perp e^{coal} \ge 0 \\
& \lambda \ge 0 \ \ (= 0 \ \ if \quad e^{wind} < \bar{e}^{wind}) \\
& \beta \ge 0 \ \ (= 0 \ \ if \quad e^{wind} > W) \\
& \gamma \ge 0 \ \ (= 0 \ \ if \quad e^{coal} < \bar{e}^{coal})
\end{aligned} \tag{5.12}
$$

Taking into account our assumptions of $e^{wind} > 0$, $e^{coal} > 0$ and the property of $p'(e) < 0$, the conditions of (5.12) can be rewritten as:

$$
\begin{aligned}
& p = c'(e^{wind}) + \lambda - \beta - p' \cdot (e^{wind} + e^{coal}) \Rightarrow p > c'(e^{wind}) + \lambda - \beta \\
& p = c'(e^{coal}) + \gamma - p' \cdot (e^{wind} + e^{coal}) \Rightarrow p > c'(e^{coal}) + \gamma \\
& \lambda \ge 0 \ \ (= 0 \ \ if \quad e^{wind} < \bar{e}^{wind}) \\
& \beta \ge 0 \ \ (= 0 \ \ if \quad e^{wind} > W) \\
& \gamma \ge 0 \ \ (= 0 \ \ if \quad e^{coal} < \bar{e}^{coal})
\end{aligned} \tag{5.13}
$$

Let us suppose that the monopolist faces the same overall demand function, cost functions, and energy capacities as that in the competitive case, and the mandated targets are same in these two markets. Comparing the monopolistic conditions of (5.13) with the competitive conditions of (5.9), it is not hard to conclude: suppose that the electricity outputs consumed in monopolistic case are identical to that consumed in competitive case, then the market price chosen by the monopolist must be higher than the price set by competitive market. For this reason, consumers will typically be worse off in a market organized as a monopoly than in one organized competitively. In other words, the monopolistic case is inefficient.

6 Discussion

As we have mentioned in first two chapters, wind power electricity should be developed in China because it is a good alternative to meet the increasing demand of electricity and it is not harmful to both global and local environment. It is reasonable to believe that China would be better off if wind power electricity develop on a larger scale.

6.1 Why MMS

Some studies indicate that high costs are the key barriers to the restraint of the expansion of wind power in China. According to the World Bank (2001) in the development of wind power, there are three important stages which developed countries traditionally have gone through. They are: technology development, cost reduction, and market building. In technology development stage, countries focused on developing technology and making it reliable. Usually, they were devoted themselves to the domestic wide-scale manufacture of large, high-quality turbines. Once the technologies were mature, the focus shifted to cost reduction. In cost reduction stage, countries might encourage further technological development and seek fiscal or other incentives to reduce the wind power's cost. When the technologies were reliable and the cost reduction was achieved, the market for wind power would be ready for growing substantially. The most direct way to create a market is through a legal requirement on supply or purchase of wind power electricity. The legal requirement is demonstrated an effective approach taken by world-leading wind power countries to develop wind power industry. Two fundamentally different policy regimes are always introduced. One is that the government sets the price and the market determines the quantity (such as German Feed-in Law); the other is that the government sets quantity and the market determines the price (such as MMS we are discussing).

In this study, we suggest implementing MMS policy in the modeled power market but not Feed-in Law or the same kind of policies for following reasons:

Firstly, in general, markets are more efficient than governments in setting prices. Learning from some countries' experience, we know it is difficult to readjust prices downward once the relative higher price is set by the government (Lewis, J. & Wiser, R., 2005). Secondly, the allocation of price difference is a difficulty. According to the current status for Chinese power market, after the separation of generation and transmission, the profits gained by grid companies are not high enough to afford this price difference. On the other hand, China is still a developing country, and people's living standard in China is still lower than that in developed countries. If the government mandates that wind power electricity has to be bought at a certain price which is generally higher than the regular market price for conventional power, it is hardly possible for people to voluntarily choose to pay an extra rate for the green electricity. An extra rate actually implies an increasing cost of living burden which ordinary people may not be able to afford. Last but not least, the legal system of the Chinese power industry is not strong and mature enough. In the market with an imperfect legal system, if there are two different prices existing, it will provide some conventional power producers with a loophole to strive for private benefits though deception. For instance, the coal-fired power producer may pretend itself to be a wind power producer to get round the laws or regulations and to make profit by selling coal-fired's electricity at wind's price. These possibilities must deviate from the original intention of the policies and impair the healthy development of wind power.

6.2 Recommendations for Inner Mongolia

We now take Inner Mongolian power market as an example to make some policy suggestions. We choose Inner Mongolia because it is reasonable to say that the modeled market can simply represent Inner Mongolian power market where the wind power and coal-fired power are simultaneously produced.

6.2.1 Some facts in Inner Mongolia

Inner Mongolia Autonomous Region is one of the earliest provinces or regions to develop wind power and it offers the biggest development potential for wind power in China. It possesses a considerable wind resource. Its total reserve is up to 1,010 GW, containing 1/3 of national wind resources, and the exploitable capacity is more than 100 GW (ICOSEPRI, 2006). Its wind resource has the properties of stability and continuity. The areas in rich wind resource are stretching from northwest to northeast, accounting for 80 percent of the whole autonomous region. The average yearly wind speed in these areas is 3-4 meters per second. Its yearly available hours with effective wind speed can be 5,000 hours, and it even could be more than 7,000 hours in some area. Meanwhile, the longest yearly continuous hours with non-effective wind speed is less than 100 hours (ICOSEPRI, 2006). By the end of 2005, Inner Mongolia has already had 6 large-size wind plants with the total installed capacity of 16,574 MW, which is ranked second in China (Shi, 2006).

Additionally, Inner Mongolia is the second-large coal base in China, just behind Shanxi province. It not only has an abundant coal resource with the total reserve of 10 gigatons (GT), but also has a relatively low cost for exploitation (Li, 2005, September 28). According to sources of local government, Inner Mongolia aims to be the country's largest coal producer by 2010 (Li, 2005, September 28).

Last but not least, being a pioneer province for developing wind power, the market for wind power is relatively matured in this region. Inner Mongolia has applied a government-direct pricing policy for a long time. It issued the regulation in 1995 to set the purchasing price for wind power at 0.731 Yuan / kwh (including VAT); 0.609 Yuan / kwh (excluding VAT). To support the development of wind power, Inner Mongolia government made great efforts. Subsidies are often provided by Chinese government to support renewable energy. In 1986-1990, Inner Mongolia government provided consumers with a subsidy of 200 Yuan per set of 100 Watts wind power system. Besides subsidies, it also arranged 400 million Yuan favorable loans to support its wind power and reduce the value-added annex tax (VAAT) from 8% to 3% (NREL, 1999). However, it has not yet developed a sizable market for wind power, though efforts are under way to achieve this goal.

6.2.2 Recommendations

According to the 10th Five Year Plan, the wind development target for Inner Mongolia is 300 MW by the end of 2010 (the World Bank, 2001). Although we can not provide specific details on how much the mandated target should be set each year due to the limitation of this study, we could make the following suggestions on implementation of such MMS policy in Inner Mongolia.

Note that Inner Mongolia is still in the earlier stage to develop wind power. Considering it's current market conditions, it should firstly establish a minimum amount of generation to be supplied from wind power through comprehensive legislation. The legislation should detail, for example, reasonable level wind power capacity during a certain period, the governmental subsidies for electricity supplied from wind power or fees for electricity from coal-fired power. This is tried and true measured in many countries.

Additionally, many developed countries have spent a lot in research and development (R & D) of wind power technologies. China is behind these countries. In China, local governments rarely carry out R & D activities, almost all those activities are supported by central government. In order to promote sustainable wind power development, therefore, we suggest that wind power R & D should be listed as part of wind power projects. Although Inner Mongolia maybe has no advantage in manufacturing turbines, it can do other R & D activities such as: market analysis, policy studies and economic feasibility studies.

Moreover, it is noticed that financial and tax incentives are good instruments to manage and regulate energy structure. One option, for instance, is to remove subsidies for coal.

Usually, these incentive measures are established and directed by central government. Local governments have little space to adjust them. For local government, therefore, it becomes more important to provide the central government with reliable data, and urge it to use the policy instruments moderately. We would like to suggest some incentive policy options to support MMS. 1) Extend the exemption period of income tax for wind power technologies, for example, to five years; 2) Reduce the existing VAT (8%) imposed on wind power at least equal to the coal-fired's.

7 Conclusion

7.1 Summary

In China, coal has been supported and subsidized for decades. As a result, coal-fired power plants are relatively inexpensive to build and fuel. Wind power, on the other hand, is still considered expensive compared to the competition (Lew, D. & Logan, J., 2001). Recalling the analyses in Section 4.1, and in Case II, IV, VI and VIII in Section 4.2, we conclude that if the market price were greater or equal to the wind power's marginal cost at the optimal allocation point, the optimal allocation would be the same no matter MMS policy would be introduced or not. However, the condition that market price is greater or equal to the wind power's marginal cost at the optimal allocation point is hardly satisfied by the current market except for CDM projects. In other words, if wind power industry could develop in a certain large-scale with a low enough marginal cost curve so that the market price can be equal to or even higher than its marginal cost at the optimal allocation point, MMS policy would be redundant.

Additionally, based on the analyses in Case I, III, V and VII in Chapter 4 we conclude that under the current market condition that the marginal cost of wind power may be higher than the market price at the optimal allocation point, we need MMS policy to make a positive wind power output possible. Of course, this does not mean that a positive wind power target must be realized without any supporting measures. The supporting measures are necessarily needed to assist in implementing MMS. These supporting policies could be the direct governmental subsidies for this green power, and other fiscal instruments like Value Added Tax (VAT) reduction and technology development support, etc.

According to the analyses in Chapter 5, we conclude: firstly, if the overall demand curve, the marginal cost curves, the upper generation capacity curves, and the mandated target faced by the producers in competitive case are the same as those in the social optimization problem, the competitive market will sustain the social solutions; additionally, if the electricity outputs consumed in monopolistic case are the same as that consumed in competitive case, the market price chosen by the monopolist must be higher than the price set by competitive market. That is the competitive structure with MMS is more efficient than the monopolistic one.

7.2 Limitation and suggestions for further studies

Limitations in this study arise mainly from the capacity of a master thesis and the collection of necessary data. The scale for a master thesis is limited, not only in terms of the time span, but also of the issue chosen and included for discussion. This is very much what it has been faced with when this study was being done. Admittedly, there are a wide variety of important issues which are covered by the topic of wind power; however, it is highly impossible to cover all of them within one thesis. Therefore, the MMS policy regime on promoting wind power was selected as the focus of this study. For lack of the relevant power costs data, the model in this study is theory-based one. We may further investigate to set the target of an MMS by using cost- benefit analysis if the necessary data can successfully be collected. However, taking account of the similar properties among wind power and other renewable flow resources, the model in this study, may also applied to investigating these resources, such as solar, wave and geothermal power.

There are, of course, some improvements or other aspects in the economic analysis of MMS policy that would be interesting for further discussion. The followings are some examples:

Firstly, in my study, to simplify the problems we temporarily take the damage from using coal-fired power, $d(e^{coal})$, as zero. An improvement study can be done to analyses the problems by considering the external cost

Secondly, we said the supporting measures are necessary for implementing MMS policy.

For further study, we would investigate what the supporting measures could be on earth? And what are the advantages and disadvantages for these would-be supporting measures?

Last but not least, in my study, we investigated the market where only wind power and coal-fired power are used simultaneously. However, a study adding other energy resource, such as hydro power, can be done to investigate how the MMS functions in that more complicated model.

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